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USE OF DIESEL ENGINES IN TUNNELS

BY

S. H. ASH AND L. L. NAUS

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UNITED STATES DEPARTMENT OF THE INTERIOR - BUREAU OF MINES

USE OF DIESEL LOCOMOTIVES IN TUNNELS[1]

By S. H. Ash[2] and L. L. Naus[3]

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INTRODUCTION

Probably one of the most significant departures in tunneling practice is the introduction of Diesel locomotives for haulage (Diesel trucks have been used for some time). The fallacy of the belief that they do not generate carbon monoxide or toxic gases and can be used indiscriminately has been proved by the authors through observation for several years of atmospheric conditions surrounding the use of Diesel engines in tunnels.

Diesel locomotives have been introduced in tunnel haulage for reasons other than safety or health. Except to the extent that they replace trolleys, with their danger of causing electrocutions, modern Diesel locomotives do not increase safety or remove any ordinary hazards to safety or health. In fact, they create such hazards, the extent of which is limited entirely by the carbon monoxide-control level set, method of ventilation, adequacy of the measures taken to prevent ignition of explosive gas, compliance with regulations, and frequency and efficiency of inspection by the management and Government enforcement agencies.

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[1] The Bureau of Mines will welcome reprinting of this paper, provided the following footnote acknowledgment is used: "Reprinted from Bureau of Mines Information Circular 7222."
[2] Supervising engineer, District B, Bureau of Mines, Wilkes-Barre, Pa.
[3] Engineer-in-charge, Bureau of Mines, Albany, N. Y.

Most important to the tunnel operator are (1) the hazards presented by the actual operation of Diesel engines underground; (2) the amount of fresh air required to operate such an engine; and (3) the means that can be taken to indicate the presence or absence of toxic gases in the atmosphere when Diesel engines are used underground.

It is believed that the observations reported in this paper will serve as a basis for safer operation of Diesel engines underground.

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For assistance in obtaining material and preparing this report the authors are indebted to R. W. Remp, general superintendent, Dravo Corporation, and Fred W. Stiefel, chief engineer and manager, Samuel R. Rosoff, Ltd., on the Delaware Aqueduct tunnels; D. Harrington, chief, Health and Safety Branch, and J. J. Forbes, supervising engineer, Safety Division, H. H. Schrenk, chief chemist, Health Division, and John C. Holtz, senior explosives engineer, Federal Bureau of Mines; Gustav Werner, supervising inspector, Bureau of Mines, Tunnels, Quarries, and Explosives, New York; Leonard Greenburg, M. D., executive director, Theodore Hatch, associate dust-control engineer, and William B. Harris, assistant dust-control engineer, Division of Industrial Hygiene, New York Department of Labor; and the superintendents, foremen, safety engineers, workmen, and others at the various tunnels visited for information supplied and hearty cooperation.

HAZARDS IN USE OF DIESEL ENGINES

Recent observations by the authors indicate that it is extremely dangerous to operate even the best available Diesel locomotives in tunnels lacking adequate ventilation.

As the kind of fuel burned in Diesel locomotives depends on a fixed amount of oxygen in air by weight, the use of such equipment in high altitudes requires that the percentage of oxygen (by volume) in the general tunnel air be kept virtually normal and that the fuel:air ratio be adjusted to fit local conditions, as it is the fuel:air ratio attainable at maximum power output or full throttle that is significant. The composition of exhaust gases from Diesel engines in proper mechanical condition has been determined.[4]

Diesel engines used in tunneling operations are worked to their capacity at high speeds and at full load or nearly so. The composition of exhaust gases as revealed in laboratory tests is of interest, as such tests indicate the results of controlled operation rather than those that probably would be obtained under the handicaps and variations in procedure and requirements of actual operation. Furthermore, the amount of carbon monoxide and other gases produced depends on the actual horsepower developed by the engine as well as on other factors.

Owing to their toxicity, oxides of nitrogen, carbon monoxide, carbon dioxide, and oxides of sulfur (if the fuel contains sulfur) in the exhaust are the chief constituents of significance to the purity of the atmospheric air of tunnels. The hazards from oxides of sulfur may be avoided by using a fuel containing little or no sulfur.

It is a common belief that Diesel engines do not generate carbon monoxide,[5] although it is recognized that the fumes they produce are nauseating to breathe. The atmosphere in a confined place may become very dangerous in a strikingly short time if Diesel engines are operated without an adequate supply of normal air. Atmospheres that could be fatal in 30 minutes or less owing to the presence of toxic gases such as are generated by Diesel engines need contain only 30 percent carbon dioxide, 0.5 to 1.0 percent carbon monoxide, or 0.07 percent oxides of nitrogen (by volume).[6]

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[4] Holtz, J. C., Berger, L. B., Elliott, M. A., and Schrenk, H. H., Diesel Engines Underground. I. Composition of Exhaust Gases from Engines in Proper Mechanical Condition: Bureau of Mines Rept. of Investigations 3508, 1940, 48 pp.
Berger, L. B., Elliott, M. A., Holtz, J. C., and Schrenk, H. H., Diesel Engines Underground. II. Effect of Adding Exhaust Gas to Intake Air: Bureau of Mines Rept. of Investigations 3541, 1940, 18 pp.
Elliott, M. A., Holtz, J. C., Berger, L. B., and Schrenk, H. H., Diesel Engines Underground. III. Effect on Exhaust-Gas Composition of Operating Engines in Mixtures of Normal Air and Natural Gas: Bureau of Mines Rept. of Investigations 3584, 1941, 50 pp.

[5] Richardson, Harold W., and Mayo, Robert S., Practical Tunnel Driving: McGraw-Hill Book Co., Inc., 1941, p. 136.

[6] Perrott, G. St. J., Babcock, L. W., Bitting, C. D., and Jones, G. W., Toxic Gases from 60-Percent Gelatin Explosives: Bureau of Mines Tech. Paper 482, 1931, 30 pp. (p. 14).

From the foregoing it can be observed that oxides of nitrogen are 10 times more deadly than carbon monoxide and 430 times more deadly than carbon dioxide. An atmosphere containing 0.09 percent carbon monoxide by volume will produce unconsciousness in 1 hour. In 1 hour a Diesel engine operating under a load of 100 brake-horsepower may produce about 1,602 cubic feet of carbon dioxide, 9.072 cubic feet of oxides of nitrogen, and 3.552 cubic feet of carbon monoxide. If ventilation is stopped for 1 hour and the Diesel engine is operated continuously, enough toxic gases would be produced to make a deadly atmosphere of nearly 100,000 cubic feet in a tunnel. Therefore, a tunnel should not only be well-ventilated if Diesel engines are to be used, but atmospheric conditions should be checked constantly with precise testing equipment.

The presence and source[7] of more than normal amounts of carbon dioxide in the atmosphere in all types of underground openings are generally known. Although its presence is important, and excessive amounts should be avoided if possible in any operation, the situation is entirely different when Diesel engines are used underground, as such engines in operation are constantly generating large quantities of carbon dioxide that are additive to that already present when engines are not in operation. As Diesel engines must obtain their supply of air from the atmosphere of the tunnel, a definite limit should be placed upon the concentration of carbon dioxide present, as its presence materially affects the fuel:air ratio, and there is a marked increase in the concentration of carbon monoxide.

Results of experiments[8] emphasize the importance of maintaining at all times the concentration of carbon dioxide and oxygen in the atmosphere within the specified permissible limits, because decidely hazardous conditions result when the intake mixture contains more than 1 percent carbon dioxide or less than 19 percent oxygen. These limits should not be accepted as a dividing line between safe and unsafe conditions but rather as emphasizing the necessity of keeping the carbon dioxide concentration below 1 percent and the oxygen above 19 percent. The authors believe that the carbon dioxide concentration in the general tunnel air where Diesel engines are used should not exceed 0.5 percent (preferably 0.3 percent) nor the oxygen concentration be less than 20 percent.

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[7] Burrell, G. A., Robertson, I. W., and Oberfell, G. G., Black Damp in Mines: Bureau of Mines Bull. 105, 1916, 92 pp.
Harrington, D., and Ash, S. H., Some Essential Safety Factors in Tunneling: Bureau of Mines Bull. 439, 1941, 31 pp.
Harrington, D., and Denny, E. H., Gases That Occur in Metal Mines: Bureau of Mines Bull. 347, 1931, 21 pp.

[8] Berger, L. B., Elliott, M. A., Holtz, J. C., Schrenk, H. H. Diesel Engines Underground. II. Effect of Adding Exhaust Gas to Intake Air: Bureau of Mines Rept. of Investigations 3541, 1940, 18 pp.

Results of Bureau of Mines laboratory tests[9] show clearly that the quantities of carbon monoxide, oxides of nitrogen, and aldehydes produced by Diesel engines when the engine intake contains inflammable gas are much greater than when the intake is nearly normal air.

The Bureau of Mines[10] recommends that the percentage of inflammable gas in the atmosphere be less than 0.25 percent (2,500 parts per million) when internal-combustion engines are in use underground.

On August 19, 1941, the Division of Industrial Hygiene,[11] New York State Department of Labor, issued rules governing the use of Diesel engines underground and stipulated that only locomotives classified as "permissible" by the Federal Bureau of Mines may be used if explosive gas in concentrations greater than 0.4 percent of its lower limit (0.02 percent methane) is present in the main air current.

Experience[12] has shown that the use of Diesel locomotives in gassy or inadequately ventilated underground workings definitely creates hazards that may cause an explosion, a fire, or the asphyxiation of a large number of workmen.

Modern engines cannot be operated safely in atmospheres containing more than small amounts of methane, owing to the hazard from explosions in explosive mixtures and a rapid increase in toxic and irritating gases if more than a relatively small amount of methane is present. A Diesel engine cannot be operated safely in an atmosphere containing more than 1 percent carbon dioxide, an amount that otherwise might not be dangerous. A Diesel engine, therefore, cannot be operated safely in an atmosphere deviating only slightly from normal, and it would not only be useless but dangerous and impossible to operate a Diesel locomotive for recovery work or other purpose in a mine or tunnel following a fire or an explosion, when ventilation has stopped or is deficient, or in situations in which an outburst of methane or carbon dioxide gas is likely to occur. Any Diesel engine constitutes a fire hazard.

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[9] Elliott, M. A., Holtz, J. C., Berger, L. B., and Schrenk, H. H. Diesel Engines Underground. III. Effect on Exhaust-Gas Composition of Operating Engines in Mixtures of Normal Air and Natural Gas: Bureau of Mines Rept. of Investigations 3584, 1941, 50 pp.

[10] Mine Safety Board, Recommendations of the United States Bureau of Mines in Certain Questions of Safety as of October 1, 1936. Decision 19: Bureau of Mines Inf. Circ. 6946, 1937, 45 pp.

[11] Harrington, D., and Ash, S. H., Some Essential Safety Factors in Tunneling: Bureau of Mines Bull. 439, 1941, 61 pp.

[12] Breyre, Ad., and Fripiat, J., Diesel Locomotives in Gassy Mine Workings of Belgium: Bureau of Mines Rept. of Investigations 3527, 1940, 17 pp.

ATMOSPHERIC CONDITIONS IN TUNNELS WHERE DIESEL ENGINES ARE USED

The authors have been observing atmospheric conditions in connection with the actual operation underground of 10 Diesel mine locomotives in nongassy and gassy tunnels of the Delaware Aqueduct since the first of them was placed in service on August 7, 1939. These locomotives are equipped with a 6-cylinder Hercules Diesel engine, Model DHXB, 5-inch bore and 6-inch stroke, having a piston displacement of 707 cubic inches, rated at 160 brake-horsepower at 1,600 r.p.m. One of these locomotives was tested before the 10 were introduced in these tunnels.

Observations in gassy tunnels have been few but sufficient with the aid of analyses of tunnel-air samples taken in the same tunnels before and after the introduction of Diesel engines to show that there is no apparent change in the composition of tunnel-air constituents when the methane content is kept at the level required by State law.

The authors made several hundred tests of the tunnel atmospheres with a supersensitive as well as an ordinary carbon monoxide indicators. It has been observed that conditions as to carbon monoxide content, aldehydes, and visibility are noticeably worse under a blower system of general ventilation than under an exhaust system when Diesel locomotives are used during excavating operations. Whether the Diesel engine is used with a truck, tractor fan, mucking machine, or locomotive, air analyses and observations of atmospheric conditions indicate that certain requirements for the control of atmospheric conditions cannot be based upon permissible toxic gas limits set for physiological reasons alone, as these do not fit the tunnel workers who labor strenuously for long periods in atmospheres and under conditions not comparable with procedure that has been followed in establishing accepted permissible limits for toxic gases.

The authors have observed atmospheric conditions when Diesel engines were used in tunnels that contained no gas-bearing strata and whose atmosphere, therefore, could be essentially normal air. However, for various reasons ventilation was deficient or inadequate during operation of the Diesel equipment, and atmospheric conditions varied accordingly.

The following observations were made regarding the condition of the general tunnel air when Diesel engines were used:

When the concentration of carbon monoxide is 0.01 percent and that of carbon dioxide 0.3 percent, visibility is poor to bad, and the aldehydes and other irritants are obnoxious after a relatively short exposure.

When a Diesel locomotive is run until the concentration of carbon monoxide is 0.01 percent and that of carbon dioxide is 1 percent, visibility is blanked out and the odors are sickening. When an ordinary Diesel truck is used, this condition is achieved with 0.003 to 0.005 percent carbon monoxide and 0.3 percent carbon dioxide.

When the concentration of carbon monoxide is 0.0015 to 0.0025 percent and that of carbon dioxide 0.15 percent, conditions are only fair at best and often are bad.

When men are subjected to carbon monoxide from blasting in concentrations ranging from 0.01 to 0.1 percent for 2 hours, and to intermittent exposure to 0.001 percent carbon monoxide and less than 0.13 percent carbon dioxide from the operation of Diesel engines, they may and do complain but will tolerate the condition.

When men are not subjected to carbon monoxide ranging from 0.01 to 0.1 percent following blasting operations, they will become accustomed to conditions that accompany the use of Diesel engines in normal air when the carbon monoxide concentration ranges from 0.001 to 0.002 percent and that of carbon dioxide averages about 0.13 percent.

Table 1 summarizes analyses of tunnel-air samples and tests conducted by the authors in connection with underground operation of Diesel locomotives during lining operations.

Diesel locomotives operate under maximum demand during lining operations; and, considering the ton-miles involved, it is believed that this study gives a fair picture of what can be expected of modern Diesel locomotives when operated in virtually normal air.

In table 1 the conditions have been broken down as far as possible and the samples discussed are representative of actual operating conditions based upon maximum and reasonable safety. Attention is called to certain conditions that enter into the calculations:

Sample 1 was taken in the north heading of shaft B, where a Diesel locomotive was in use while mucking out for invert was in progress, before samples 2, 3, 4, and 5 were collected in the south heading of shaft B, where arch lining was being poured. Sample 1 showed the presence of 0.09 percent CO_2, -0.0001 percent CO, and 0.0002 percent oxides of nitrogen. It will be noted that 55,000 c.f.m. of air was flowing from shaft A to shaft B, where the air current split, with the measured amounts, as shown, ventilating the south heading of shaft B and the remainder passing to the surface through upcasting shaft B. This fact has been considered in calculating the toxic gases added to the atmosphere in the south heading.

TABLE 1. - Results of tests of atmospheric conditions in tunnels in which Diesel locomotives are used

Sample No.	Analyses, percent by volume						Toxic gases added					
							Percent by volume			C. F. M.		
	CO_2	O_2	CO	CH_4	N_2	NO_x[10]	CO_2	CO	NO_x[10]	CO_2	CO	NO_x[10]
1	0.09	20.91	-0.0001	0.03	78.97	0.0002	0.06	-0.0001	0.0002	33.00	-0.0550	0.1100
2	.12	20.80	-.0001	.04	79.04	.0010	.06	-.0001	.0008	23.16	-.0386	.3080
3	.21	20.41	[2] .0010	.03	79.35	-	.15	+.0009	-	57.90	+.3474	-
4	.14	20.76	.00075 to [3] .00150	.04	79.06	.0004	.08	+.00065 to +.00140	.0002	30.00	+.2437 to +.5250	.0750
5	.15	20.76	.0005 to [4] .0010	.03	79.06	-	.09	+.0004 to +.0009	-	33.30	+.1480 to +.3330	-
6	.13	20.85	-.0001	.02	79.00	.0008	.10	-.0001	.0008	38.64	.0386	.3091
7	.10	20.90	.00075 to [5] .00150	.02	78.98	.0008	.07	.00075 to .00150	.0008	27.02	.2895 to .5790	.3088
8	.16	20.84	[6] .00075	.02	78.98	.0007	.13	.00075	.0007	52.00	.3000	.2800
9	.10	20.87	-.0001	-	79.03	.0003	.07	-.0001	.0003	30.10	.0043	.1290
10	.12	20.82	.0001 to [7] .0005	-	79.06	.0003	.09	.0005	.0003	38.70	.0430 to .2150	.1290
11	.09	20.92	[8] .0005	-	78.99	.0003	.06	.0005	.0003	26.16	.2180	.1308

See footnotes p. 13.

TABLE 1. - Results of tests of atmospheric conditions in tunnels in which Diesel locomotives are used (Cont'd.)

Sample No.	Analyses, percent by volume						Toxic gases added					
							Percent by volume				C. F. M.	
	CO_2	O_2	CO	CH_4	N_2	NO_x 10/	CO_2	CO	NO_x 10/	CO_2	CO	NO_x 10/
12	0.03	20.93	-0.0001	-	79.04	0.0003	-	-0.0001	0.0003		-0.2574	0.7722
13	.05	20.92	-.0001	-	79.03	.0007	0.02	-.0001	.0004	5.76	.0288	.1152
14	.06	20.88	.0003	-	79.06	.0014	.03	+.0002	.0011	8.25	+.0550	.3025
15	.13	20.79	.0002 to .0010	-	79.04	-	.10	+.0001 to +.0009	-	10.00	+.0100 to +.0900	-
16	.16	20.72	.0002 to 9/.0015	0.04	79.08	.0017	.13	.0002 to .0015	.0017	44.85	.0690 to .5175	.5865
17	.06	20.86	-.0001	.02	79.06	-	.03	-.0001	-	9.00	-.0300	-
18	.06	20.89	-.0001	.02	79.01	.0005	.03	-.0001	.0005	10.50	-.0350	.1750
19	.12	20.88	.0005	-	79.00	-	.09	.0005	-	18.90	.1050	-
20	.20	20.83	.0005 to .0007	-	78.97	.0013	.17	.0005 to .0007	.0013	34.00	.100 to .140	.260

See footnotes p. 13.

TABLE 1. - Results of tests of atmospheric conditions in tunnels in which Diesel locomotives are used (Cont'd.)

Sample No.	Ventilating current		Average horse-power output	Volume (cubic feet) of toxic gases added per average horsepower			Remarks
	c.f.m.	Direction[1]		CO_2	CO	NO_x[10]	
1	55,000	+	120	0.275	-0.000459	0.000917	1 locomotive operating 75 percent of time mucking out invert. Air current enters through downcast shaft A, flows south to shaft B, where it splits, 1 split upcasting through shaft B and the other ventilating the south heading of shaft B.
2	38,600	+	120	.193	-.000321	.002240	1 locomotive operating 75 percent of time pouring concrete arch lining.
3	38,600	+	240	.213	+.000723	-	3 locomotives in use pouring concrete arch lining.
4	37,500	+	120	.250	+.000730 to +.001640	.000625	1 locomotive in operation 75 percent of time pouring concrete arch lining.
5	37,000	+	160	.208	+.000462 to +.001041	-	2 locomotives operating 50 percent of time during change of trips at shaft-bottom loading station while pouring concrete arch lining.
6	38,640	+	120	.322	-.000321	.002570	1 locomotive in operation 75 percent of time pouring concrete arch lining.
7	38,600	+	120	.225	.000904 to .001809	.002570	Do.
8	40,000	+	160	.325	.001874	.001750	1 locomotive in constant operation pouring concrete arch lining.

See footnotes p. 13.

TABLE 1. - Results of tests of atmospheric conditions in tunnels in which Diesel locomotives are used (Cont'd.)

Sample No.	Ventilating current		Average horse-power output	Volume (cubic feet) of toxic gases added per average horsepower			Remarks
	c.f.m.	Direction1/		CO_2	CO	NO_x10/	
9	43,000	+	120	0.251	-0.000358	0.001080	1 locomotive in operation 75 percent of time pouring concrete arch lining.
10	43,000	+	120	.322	.000358 to .001790	.001075	Do.
11	43,600	+	160	.163	.001360	.000820	1 locomotive with engine idling at shaft-bottom loading station during change of trips.
12	25,740	-	-	-	-	-	Samples collected in finished tunnel (north heading, shaft D). Air current enters at shaft C and flows south to shaft D. No locomotive operating in air current; presence of toxic gases probably due to reversal of air current during shift and before sampling.
13	28,800	-	160	.0360	-.000180	.000720	1 locomotive operating in air current for 4 minutes during change of trips at bridge for pouring concrete arch lining. Air current traveling from finished tunnel toward unlined tunnel; locomotive traveled less than 1,000 feet from sampling point outby bridge.
14	27,500	-	160	.0516	+.000344	.001890	1 locomotive operating 100 percent of time.

See footnotes p. 13

TABLE 1. - Results of tests of atmospheric conditions in tunnels in which Diesel locomotives are used (Cont'd.)

Sample No.	Ventilating current		Average horse-power output	Volume (cubic feet) of toxic gases added per average horsepower			Remarks
	c.f.m.	Direction 1/		CO_2	CO	NO_x 10/	
15	10,000	-	160	0.0625	0.000063 to .000562	-	1 locomotive operating in air current for 4 minutes during change of trips at bridge for pouring concrete arch lining. Air current traveling from lined to unlined section of tunnel. Air current very sluggish.
16	34,500	-	204	.220	.000338 to .001078	0.002852	2 locomotives in use 66 percent of the time.
17	30,000	-	160	.0563	-.000188	-	1 locomotive operating in air current for 4 minutes during change of trips.
18	35,000	-	107	.0939	-.000327	.001635	2 locomotives operating 33 percent of time while concrete arch lining was being poured. 2 Diesel locomotives and 1 storage-battery locomotive used for transporting trains at agitators.
19	21,000	+	160	.1181	.000656	-	1 locomotive operating about 100 percent of the time.
20	20,000	+	204	.1670	.000490 to .000686	.001274	2 locomotives each operating about 66 percent of the time while concrete arch lining was being poured.

See footnotes p. 13.

Footnotes to Table 1

1/ Direction of air current: - = air flow from lined to unlined section of tunnel; + = air flow from unlined to lined section of tunnel.
2/ CO indicator reading at time trips changed on bridge with 3 locomotives in operation, calculation based upon 480 horsepower. Samples of air collected after change of trips with two locomotives in operation 75 percent of the time.
3/ Reading taken at change of trips with 2 locomotives in operation; calculation based upon 320 horsepower. Samples collected following test with CO indicator.
4/ Reading taken with 2 locomotives in operation during change of trips; calculation based upon 320 horsepower.
5/ Locomotive, with engine idling, on bridge at time of test.
6/ Locomotive, with engine idling, just after arriving at shaft-bottom loading station.
7/ Locomotive, with engine idling, on bridge when maximum amount of CO was recorded. Air samples collected after trip left bridge.
8/ Locomotive engine idling.
9/ 0.0015 percent CO recorded at change of trips with 3 locomotives in operation for which reason 480 horsepower is used in calculating c.f.m. per horsepower at maximum. Samples collected after change of trips.
10/ NO_x = Oxides of nitrogen.

A similar condition existed in the north heading of shaft D, where sample 12, taken in the finished tunnel, showed the presence of 0.0003 percent oxides of nitrogen and -0.0001 percent CO, although no Diesel locomotive was operating in the air current north of the bridge. On this day the air current entered through shaft C and flowed south through the finished tunnel into the unlined section, where it discharged at the surface through upcast shaft D. Allowance for the above concentrations of oxides of nitrogen and CO in the atmosphere was made in calculating the toxic gases added to the ventilating current by the operation of Diesel locomotives, as shown by the analyses of samples 13 and 14.

The average horsepower output of the Diesel locomotives used in calculating the cubic feet per minute per horsepower of toxic gases added is based upon the approximate time they were in operation; and this, in turn, is based upon the approximate time the train would be in transit between points in that particular section of the tunnel ventilated by the air current in which the samples were collected. It was assumed that the locomotives operated at maximum speed while in transit.

Data included in the field notes made it possible to establish whether or not the locomotive engines, when present, were stopped or idling at the time of sampling.

Samples collected and tests made where more than one locomotive was in use may be confusing if it is assumed that all locomotives were in operation all of the time and all were operated in the air current being sampled. Such an assumption may be incorrect, because even though three locomotives were in use for lining, it was established that in some instances not more than one of them was in use at the particular time samples were collected. The locomotive in the air current sometimes did not operate for more than a few minutes.

Upon the basis of investigations by the authors in cooperation with engineers of the Division of Industrial Hygiene, New York State Department of Labor, which also confirm the above observations of general tunnel-air conditions, the State of New York[13] issued requirements on December 17, 1940, covering the safe use of Diesel engines underground.

AIR REQUIREMENTS

The tunnel operator should know the minimum amount of fresh air that should be supplied to provide a safe environment if a Diesel engine is to be used underground. Analysis of data in table 1 and a review of all data available to the authors in connection with the Diesel engines observed indicate that when the engines are in good condition and operating in normal air the volumes of the toxic gases produced per minute per brake-horsepower (full load, maximum speed) are as follows: Carbon dioxide, 0.267 cubic foot; oxides of nitrogen, 0.001512 cubic foot; and carbon monoxide, 0.000592 cubic foot.

In general, the irritants, such as aldehydes, odors, and smoke, follow the trend of the toxic gases if the scrubbing devices are efficient; if they are not, the irritants are conspicuously present at all stages of operation, and the amount of oxides of nitrogen is greater.

The following calculations show one way of determining the quantity of air necessary for dilution of Diesel-engine exhaust gas, as compiled from data available to the authors in connection with Diesel engines operating in normal air (maximum speed and load) and using threshold limits[14] for toxic gases

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[13] See footnote 11 (p. 5).

[14] State of New York, Department of Labor, Toxic Gases in Mines, Tunnels and Shafts: Industrial Code, Rule 25, March 1, 1940, 10 pp.
Mine Safety Board, (Decision 9, Quantity and Quality of Air Needed in Ventilation of Coal Mines): Bureau of Mines Inf. Circ. 6946, 1937, 45 pp.
Sayers, R. R., International Critical Tables: Vol. 2, 1927, pp. 318-321.
Harrington, D., and Ash, S. H., Some Essential Safety Factors in Tunneling: Bureau of Mines Bull. 439, 1941, 61 pp.
N. Y. State Dept. of Labor, Division of Industrial Hygiene, Requirements Governing the Safe Use of Diesel Engines in Underground Operation, August 19, 1941, 3 pp.

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in concentrations that are acceptable at this time in some States: Oxides of nitrogen $\frac{40 + 33}{2}$ p.p.m.; carbon monoxide, 100 p.p.m.; carbon dioxide, 10,000 p.p.m.

The minimum rate of general ventilation or quantity of air required for dilution of any particular toxic constituent of Diesel-engine exhaust gas is obtained by the following relationships:[15]

$$Q = \frac{X}{M},$$

where Q = rate of ventilation, c.f.m.
X = quantity of toxic substance released per minute.
M = maximum permissible concentration of toxic substance per cubic foot of air in parts per million, expressed as a fraction.

With a mixed gas, such as the exhaust gas from a Diesel engine, it is apparent that an atmosphere containing any toxic substance at its maximum permissible concentration is by no means safe when it also contains other toxic substances in any amount. Therefore, an atmosphere containing a mixture of toxic substances in amounts lower than their maximum permissible concentrations is desirable.

For an atmosphere containing a mixture of toxic gases, such as nitrogen oxides, carbon monoxide, and carbon dioxide, the formula can be arranged so that:

$$Q = \frac{X\ \text{nitrogen oxides}}{M\ \text{nitrogen oxides}} + \frac{X\ CO}{M\ CO} + \frac{X\ CO_2}{M\ CO_2}.$$

When quantitative values of toxic constituents in Diesel-engine exhaust gas and permissible maxima that appear to be on the safe side are substituted in such a formula, it reads:

$$Q = \frac{0.001512}{\frac{\frac{40 + 33}{2}}{1,000,000}} + \frac{0.000592}{\frac{100}{1,000,000}} + \frac{0.267}{\frac{10,000}{1,000,000}},$$

or

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[15] Hatch, Theodore, Preventive Measures: Protecting Plant Manpower: U. S. Dept. of Labor, Div. of Labor Standards, Special Bull. 3, 1941, pp. 13-21.

Q = quantity of air required per minute per brake-horsepower = 41.4 + 5.9 + 26.7,

or

Q = 74 cubic feet per minute per brake-horsepower.

Little is known about the toxic effects of breathing a mixture of carbon monoxide and other gases.[16] Although certain critical values for carbon dioxide, carbon monoxide, nitrogen oxides, and sulfur dioxide have been accepted generally and are incorporated in a number of ventilation codes, nevertheless there is still controversy, a marked lack of agreement, and decided differences of opinion among recognized authorities as to what constitutes permissible maxima for individual toxic constituents in the atmosphere of a place of employment, and permissible maxima for mixed gases have not been established. Permissible values[17] for atmospheric control present special cases and for carbon dioxide range from 0.2 to 3.0 percent (2,000 to 30,000 p.p.m.), for carbon monoxide from 0.001 to 0.04 percent (10 to 400 p.p.m.), for nitrogen oxides from 0.001 to 0.004 percent (10 to 40 p.p.m.), and for sulfur dioxide 0.001 percent (10 p.p.m.).

Although acute poisoning from toxic gases may be fatal, nevertheless the most important hygienic risk from any poisonous substance is that which results from constant and repeated exposure.

The values more recently accepted as permissible maxima of toxic gases show a definite trend toward lower values. This is particularly true of the value for nitrogen oxides. It is observed that some authoritative bodies that have made investigations since December 16, 1936, when the Industrial Accident Commission of the State of California adopted Safety Orders controlling dusts, gases, fumes, and vapors, have suggested changes in the orders controlling harmful contaminants in atmospheric air. On November 22, 1939, this commission[18] set a maximum permissible concentration of 10 parts per million (0.001 percent) for nitrogen oxides. In discussing criteria of industrial health hazards, Drinker[19] also suggests 10 parts per million (0.001 percent) as the maximum permissible concentration for nitrogen oxides.

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[16] Harrington, D., and Ash, S. H., Some Essential Safety Factors in Tunneling: Bureau of Mines Bull. 439, 1941, 61 pp.
Mayers, May R., What We Don't Know About Carbon Monoxide: Ind. Health, Nat. Safety News, November 1939, pp. 38, 40, 86.

[17] See footnote 14 (p. 14).
Henderson, Y., and Paul, J. W., Oxygen Mine Rescue Apparatus and Physiological Effects on Users: Bureau of Mines Tech. Paper 82, 1917, p. 32.
Harrington, D., Underground Ventilation at Butte: Bureau of Mines Bull. 204, 1923, 130 pp.
Lehmann, K., and Hasegawa, (Studies on the Technical and Hygienic Action of Certain Gases on Men (XXXI). The Nitrous Gases: Nitric Oxide, Nitrogen Dioxide, Nitrous Acid and Nitric Acid): Archiv. für Hygiene, vol. 77, 1913, pp. 323-368.

If the most toxic gases (nitrogen oxides) are considered alone and taken as the controlling factor, as may be done in some jurisdictions, and the formula using the maximum permissible value of 10 p.p.m. is applied, then:

$$Q = \frac{X}{M} = \frac{0.001512}{\frac{10}{1,000,000}} = 151 \text{ cubic feet per minute per brake-horsepower.}$$

It is apparent that if this value for nitrogen oxides is generally required, the use of Diesel engines underground will be decidedly limited, except for small engines and in tunnels of large cross section. In any event, the volume of air supplied to the general tunnel air would have to be increased considerably above that commonly believed necessary.

In the time studies and tests made by the authors in connection with Diesel locomotives, the engines, during their shift of operation, produced effects in the general air that required about half the amount given above, or about 75 cubic feet per minute per brake-horsepower, based upon maximum load and maximum speed. Intermittent operation is important in tunnels of large cross section when a large volume of fresh air is stored in the bore.

There are several reasons why a Diesel locomotive can be used intermittently in actual tunneling operations and yet not produce as toxic an atmosphere as would strictly be indicated by laboratory tests. The volume of air stored in a tunnel, particularly one of large cross section, is great enough to dilute, by diffusion and mixing, a considerable volume of exhaust gas as the locomotive moves along the passageway; and as long as enough air is supplied to the general air current to dilute the exhaust gases, favorable adjustments are made in the general atmosphere as the locomotive moves to new locations. The operation of a Diesel locomotive is intermittent as between full load and no load, and as a consequence air requirements must be maximum and based upon maximum fuel consumption and maximum load. If the motor is stopped when a Diesel locomotive is not in use, the ambient air clears in proportion to the amount of fresh air in circulation.

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[18] Department of Industrial Relations, State of California, Minutes of the Industrial Accident Commission: November 22, 1939, 4 pp.

[19] Drinker, Philip, Criteria of Industrial Health Hazards: Protecting Plant Manpower: U. S. Dept. of Labor, Division of Labor Standards, Spec. Bull. No. 3, 1941, pp. 11-12.

Operation of a Diesel locomotive presents different problems, as regards ventilation, in a "heavy-construction-industry" tunnel than in a mine and even in the same tunnel, depending on the service required. The factors that contribute to these problems depend in part on whether the mining operation is intermittent (during excavation) or relatively steady (during lining operations).

During excavation the locomotive generally is used only during the mucking cycle, and the load is maximum only during haulage of loaded trains, which may or may not be favorably assisted by the grade of the bore. The most difficult situation is presented during excavation in that section of the bore lying between the car changer and the face. If the tunnel is driven singly, the most efficient ventilation can be obtained by the use of vent pipe for carrying the air current returning from the face region. During lining operations the locomotives are driven at their maximum speed and load just as long as concrete can be poured. The maximum service is demanded when the "arch" is placed, which is done without interruption if possible. If the tunnel is open, general tunnel air can be coursed through the bore in the desired direction, and all vent pipes are removed. The ventilation problem then becomes one of placing low-pressure fans in such positions as to force enough air in the proper direction. If the tunnel is blind, vent pipes must be used during lining operation and the most difficult problem arises in connection with the use of Diesel locomotives.

Operation of a Diesel locomotive also presents a different and less difficult problem from the ventilation standpoint than is presented if stationary Diesel engines are used in connection with pumps, air compressors, mucking machines, and other equipment. Use of Diesel engine-driven mucking machines presents the most serious problem if the general tunnel air is return air and the simplest problem if it is intake air and the ventilation system is supported by an auxiliary blower in the face region.

A stationary Diesel engine presents the greatest danger if it is operated at full load and ventilation is stopped, and the most favorable situation when the air current is adequate. Obviously, when a locomotive is standing still the motor can and should be stopped. Direction of flow and velocity of the air current have great bearing on the effects produced in the tunnel air during movements of a Diesel locomotive.

Stationary Diesel engines, such as compressor engines, that idle for considerable periods should have the exhaust gases led direct to the return air current if possible.

If Diesel engine-driven trucks, locomotives, and mucking machines are used simultaneously, a dual ventilation system consisting of a primary exhaust system and an auxiliary blower system is absolutely imperative in connection with excavation operations; and the blower vent pipe probably would have to be intaking in fresh air at the surface.

To insure that under no circumstances can a dangerous concentration of noxious gas be formed in the atmosphere, it is necessary for an engine to be maintained in proper mechanical condition at all times. It is not unreasonable to expect that tunnel operating men are not going to do this in all instances. Furthermore, if methane, carbon dioxide, or hydrogen sulfide are given off by the strata, their presence can materially affect the amount of toxic gases formed and therefore the amount of ventilation necessary.

The amount[20/] of air required per minute per brake-horsepower bears relation to the sum of engine-exhaust products and gas emanations from the strata and any other source of gaseous products in the general tunnel atmosphere; it is not at all improbable that such a large volume of air would be required in some tunnels and gassy mines that it would be impossible to use a Diesel locomotive for reasons of both safety and economy.

It has been shown that[21/] the amount of fresh air required to dilute the toxic constituents of Diesel engine-exhaust gas is of such magnitude, compared with the total volume of exhaust gas, that the excess nitrogen due to consumption of oxygen by the engine is insignificant in contributing to oxygen deficiency in the general air when normal air is drawn into the engine.

From field observations, data in table 1, and the formula calculations it can be concluded that at least 65 to 75 cubic feet (preferably the latter) of fresh air must be supplied per minute for each brake-horsepower developed at maximum rated speed and maximum load by a Diesel engine when operating in normal air to provide satisfactory atmospheric conditions. This amount agrees with the 10,000 c.f.m. required by the State of New York for underground Diesel locomotives of 160 brake-horsepower. Experience of the authors, State of New York Department of Labor engineers, and contractor engineers indicates

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[20/] South African Mining and Engineering Journal, vol. 52, Pt. 1, No. 2525, June 7, 1941, p. 455.
See footnotes 4 (p. 3), 14 (p. 14), and 12 (p. 5).
Colliery Guardian, Modern Diesel Pit Locomotives: Vol. 138, March 1929, 2 pp.

[21/] Berger, L. B., Elliott, M. A., Holtz, J. C., and Schrenk, H. H., Diesel Engines Underground: II. - Effect of Adding Exhaust Gas to Intake Air: Bureau of Mines Rept. of Investigations 3541, 1940, 18 pp.

that from 10,000 to 12,000 c.f.m., per 160 brake-horsepower (maximum rated speed and maximum load) Diesel locomotive, is necessary under actual operations in tunnels of about 300 square feet in cross section to keep the carbon monoxide level in the range 0.001 to 0.002 percent and thereby control the oxides of nitrogen, smoke, and aldehydes within accepted limits.

Upon the basis of supplying 75 cubic feet of normal air per minute per brake-horsepower developed, it is of interest to know the theoretical amounts of the toxic constituents possible in the general tunnel air when affected by Diesel engine-exhaust gas from locomotives operating under conditions observed. The 75 cubic feet of fresh air supplied each minute to the general tunnel air can be assumed to contain the exhaust gas produced by the engine when operating under maximum load and speed; and when equilibrium conditions are reached, the general tunnel air could contain 0.001512 cubic foot oxides of nitrogen, 0.00592 cubic foot carbon monoxide, and 0.267 cubic foot carbon dioxide. Expressed in parts per million (p.p.m.), the toxic-gas content of the general tunnel air would be 20 p.p.m. oxides of nitrogen, 8 p.p.m. carbon monoxide, and 3,560 p.p.m. carbon dioxide. Although not as pure as normal air, this atmosphere is nevertheless well within an acceptable range insofar as toxic gases are concerned, and it would be efficient for Diesel-engine intake air.

CONTROL AND MEASUREMENT OF TOXIC GASES IN GENERAL TUNNEL AIR

Although it is imperative that tunnel operators know how much fresh air is required to provide an atmosphere that will not contain an unhealthful or dangerous quantity of irritating and toxic gases and fumes as a result of operation of Diesel locomotives, it is more important to know when an unhealthful or dangerous atmosphere exists. The aldehydes and other organic compounds are very irritating to the eyes, nose, and throat. Large amounts of carbon dioxide are dangerous and definitely contribute to an increase in carbon monoxide and a deficiency in oxygen. Nitrogen, although innocuous, contributes to oxygen deficiency. The oxides of nitrogen and carbon monoxide, on the other hand, are found in very toxic quantities. These two gases usually are formed simultaneously, and an increase in one in the general tunnel air generally indicates an increase in the other when Diesel locomotives are used; the increase may be due to the use of more locomotives, to less air in circulation, or to longer running time and longer tougher hauls rather than to variations in the concentration of these gases in the engine exhaust as a result of idling of or running the engine under maximum load and speed. Diesel-locomotive motors should only be allowed to idle for very brief periods.

As measurement of the quantity of nitrogen oxides, aldehydes, and carbon dioxide and control of smoke affecting visibility in the air constitute a slow and difficult procedure and that of carbon monoxide is relatively simple, precise measurements of the latter can be and are used effectively to evaluate the quantity of toxic fumes, gases, odors, and irritants. Experience[22] has demonstrated that, as a yardstick for this purpose, acceptable conditions are attainable when the carbon monoxide concentration in the general tunnel air is kept within the range of 0.001 to 0.002 percent by volume, as indicated by a supersensitive carbon monoxide indicator.

It has been proved definitely that the level of 100 p.p.m. (0.01 percent), which is the maximum permissible concentration generally used as a yardstick for carbon monoxide, is not a safe criterion for determining the safe and healthful use of Diesel locomotives underground, and that by setting a new standard for this level in connection with such locomotives a practical means of controlling nitrogen oxides, aldehydes, smoke, other irritants, carbon dioxide, and carbon monoxide is obtained. The concentration of nitrogen oxides in the general air is the chief factor in determining safe Diesel-locomotive operation.

Objection was raised to the authors' recommendation of 0.001 percent carbon monoxide as a control level when this level was first suggested, and it was pointed out that this would establish a dual standard for the safe limit for carbon monoxide, as 0.01 is generally accepted. The fallacy of this reasoning is shown even by laboratory tests, for, if the level of 0.01 percent carbon monoxide is set for the control of atmospheric conditions when Diesel locomotives are being used underground, the nitrogen oxides could be in the region of 230 p.p.m., a very dangerous if not fatal atmosphere; and the carbon dioxide could be in the region of 41,070 p.p.m., also a dangerous atmosphere, not only from a toxic standpoint but also from the standpoint of contributing decisively to the generation of large amounts of carbon monoxide in the Diesel exhaust gas as well as to a hazardous deficiency of oxygen. On the other hand, if the yardstick of 0.001 percent carbon monoxide in the general air is used as a basis for determining the amount of air required to dilute the exhaust gas from a Diesel motor, and no more than 0.002 percent carbon monoxide is used for general air control in connection with the use of Diesel engines, one-tenth of the foregoing values for nitrogen oxides and carbon dioxide, which are within currently accepted tolerance limits, could be obtained in actual tunnel operation.

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[22] Harrington, D., and Ash, S. H., Some Essential Safety Factors in Tunneling: Bureau of Mines Bull. 439, 1941, 61 pp.
Stiefel, F. W., Operation of Diesel Locomotives Underground: Paper presented before the Meeting of Am. Inst. Min. and Met. Eng., New York City, February 1942, 14 pp.
Harris, William B., Greenburg, Leonard, and Werner, Gustav, Diesel Engines in Tunneling Operations: Paper presented before the Meeting of Am. Inst. Min. and Met. Eng., New York City, February 1942, 17 pp.

It was pointed out, also, that while the use of 10 or 20 p.p.m. of carbon monoxide may have some merit as a practical yardstick in measuring contamination by Diesel-exhaust gas, it is by no means infallible. This question is answered by the experience cited as well as by studies in Europe, where separate investigations have shown that the general air must not contain as much as 0.01 percent carbon monoxide.

In Germany,[23] experimental study of carbon monoxide formation made by several mine departments led to the following precautions:

> Special attention has to be given to the state of ventilation of all roadways in which Diesel locomotives are employed, in order to ensure that in no circumstances can a dangerous concentration of the gas be formed in the atmosphere. The concentration of carbon monoxide must not exceed between a fifteenth or twentieth of the lowest toxic concentration, i.e., about 0.0014 percent.

The experience of the authors with the use of Diesel locomotives underground in the Delaware Aqueduct tunnels indicates that for all conditions of operation, regardless of whether the engine ran at low speeds, under intermediate or high loads, or at high speeds and minimum to high loads, the ratio of concentration of nitrogen oxides to that of carbon monoxide varied, averaging about 2-1/2:1 but always greater than 1:1. Regardless of the concentration of nitrogen oxides in the general air, if the carbon monoxide concentration was 10 p.p.m. (0.001 percent), the concentration of nitrogen oxides was within the "permissible maximum" range in any jurisdiction at the present time, all of which indicates that it is a "safe" and practical yardstick, as it can be and is being complied with and, aside from protection against poisonous gases, its use is conducive to better ventilation practice.

Conditions noted recently after 2 hours of constant Diesel-locomotive operation in a long tunnel that has been using such locomotives for some time are of interest, as they probably are more representative of actual conditions in a tunnel when concrete is being poured 24 hours a day than are many others observed.

Two 160-horsepower Diesel locomotives were in the heading, and a similar locomotive was shifting cars near the supply-shaft bottom. The supersensitive carbon monoxide indicator consistently recorded 3 p.p.m. (0.0003 percent) carbon monoxide in 25,500 c.f.m. (general tunnel air), which would indicate 8,500 c.f.m. per locomotive. The atmosphere was foggy, and with this volume of air (53 c.f.m. per locomotive horsepower) the Diesel exhaust odors were very noticeable. Under existing conditions the carbon dioxide concentration was 0.06 percent, or 0.03 percent above normal. Concentration of nitrogen oxides was 14 p.p.m. (0.0014 percent).

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[23] See footnote 20 (p. 19).

It will be observed that the carbon dioxide concentration above normal was 100 times the carbon monoxide concentration, that the odor of aldehydes was strong, that the ratio of nitrogen oxides to carbon monoxide was nearly 5:1, and that the nitrogen oxide concentration was well above the 10-p.p.m. limit in effect in some jurisdictions.

This is a striking example of the value of using 0.001 percent (10 p.p.m.) carbon monoxide as a "yardstick" for the control of nitrogen oxides. For example, if ventilation was such as to allow a carbon monoxide concentration of 0.001 percent (10 p.p.m.), the concentration of nitrogen oxides would be 0.0042 percent (42 p.p.m.) and that of carbon dioxide 0.1 percent (1,000 p.p.m.). Furthermore, if the carbon monoxide concentration was allowed to attain 0.01 percent (100 p.p.m.), the concentration of nitrogen oxides would reach 0.0467 percent (467 p.p.m.) and that of carbon dioxide 1 percent (10,000 p.p.m.) - a very dangerous condition. If ventilation were increased to 75 c.f.m. per locomotive horsepower (which was recommended and done), concentration of nitrogen oxides would be 0.001 percent (10 p.p.m.), a concentration acceptable in any jurisdiction.

It can be seen that the control of noxious gases in the general air should be based upon the carbon monoxide control value of 10 to 20 p.p.m. and a minimum of 75 c.f.m. per locomotive horsepower when Diesel locomotives are operating in virtually normal air and the volume of air required per locomotive horsepower is increased to maintain a safe concentration of other gases that may result from emanations of any gas. The general tunnel air should be sampled from time to time and chemical analyses made to determine the concentration of nitrogen oxides as well as of the other gaseous constituents of the tunnel atmosphere.

This discussion shows the value of field study of Diesel locomotives in actual operation, for it was the results of field observations of atmospheric conditions that indicated the amount of carbon monoxide to be used as a yardstick for determining the quantity of air required as well as for the control of atmospheric conditions. Installation of equipment on a job cannot always wait on laboratory tests, but safety standards can be changed at any time in accordance with results obtained from collaboration in any rational approach.

The authors believe that Diesel locomotives can be used safely if kept in good mechanical condition and if adequate ventilation can be supplied so that the general tunnel atmosphere will contain not more than 0.002 percent (preferably 0.001 percent) by volume (10 p.p.m.) of carbon monoxide from Diesel engine-exhaust gas, the methane content will not exceed 0.25 percent and preferably will be less than 0.05 percent, and the carbon dioxide content will be less than 0.3 percent.

As shown in this report, the content of nitrogen oxides in the general air can be kept at 10 p.p.m. if the engine is maintained in efficient mechanical condition and the tunnel is supplied with not less than 65 cubic feet of fresh air per minute per brake-horsepower when operating in nearly normal air during excavation operations and with about 75 cubic feet per minute per brake-horsepower during lining operations. If the engine is operated in methane-air mixture, the air requirements per brake-horsepower may amount to 190 cubic feet or more of air per locomotive horsepower per minute[24] to keep the toxic gases within tolerance limits.

A Diesel locomotive requires expert attention and must be maintained in proper mechanical condition. If systematic inspections are not made and defects in the motor are not corrected immediately, serious consequences are sure to follow. The fumes are nauseating, and workmen will not long tolerate the presence of Diesel locomotives if they are not maintained properly and if enough air is not supplied to reduce the smoke, aldehydes, sulfur dioxide, and petroleum odors to virtually unnoticeable amounts. To some extent these factors act as a safety valve through the human element in maintaining the toxic gases at tolerable limits. If the atmosphere is smoky and irritating, it is a foregone conclusion that ventilation is inadequate or that engine operation is inefficient, or both.

CONCLUSIONS

The hazards of operating Diesel locomotives underground with inadequate ventilation are physical damage or loss of life from the toxic gases generated. The toxic gases in the Diesel exhaust are nitrogen oxides, carbon monoxide, carbon dioxide, and sulfur dioxide.

The controlling noxious gases are nitrogen oxides, which, under currently accepted tolerance limits, are 10 times more deadly than carbon monoxide and 430 times more deadly than carbon dioxide.

Observations of atmospheric conditions in tunnels where Diesel locomotives are in use indicate that the ratio of the concentration of nitrogen oxides to that of carbon monoxide is probably more often approximately 2.5:1, always more than 1:1 under load at any speed, and at times as high as 5:1.

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[24] See footnote 20 (p. 19).

A review of all the data available to the authors in connection with the Diesel engines observed indicates that when in good condition and operating in normal air, the volumes of toxic gases produced per minute per locomotive horsepower (full load, maximum speed) are as follows: Carbon dioxide, 0.267 cubic foot; nitrogen oxides, 0.001512 cubic foot; and carbon monoxide, 0.000592 cubic foot.

Air requirements for use of Diesel locomotives should be based not only upon the toxicity of noxious gases in the general air but also upon the fact that haulagemen at present probably have the highest accident severity rate in tunneling; therefore, a locomotive attendant should at all times be in excellent health, be alert, and have possession of all his faculties. For this reason, if no other, the question of maximum safety should be considered in providing ventilation.

From field observations made by the authors and data included in this report it can be concluded that to provide satisfactory atmospheric conditions at least 65 to 75 cubic feet (preferably the latter) of fresh air must be supplied per minute per brake-horsepower developed at maximum rated speed and maximum load by a Diesel engine when operating in normal air.

Upon the basis of supplying 75 c.f.m. of normal air per locomotive horsepower to the general tunnel air, this volume of fresh air can be assumed to contain the exhaust gases produced by the engine when operating under maximum load and speed, and when equilibrium conditions are reached in the general tunnel air the toxic-gas content could be 20 p.p.m. nitrogen oxides, 8 p.p.m. carbon monoxide, and 3,560 p.p.m. carbon dioxide.

The control of noxious gases in the general air when Diesel locomotives are being used should be based upon a carbon monoxide control value of 10 to 20 p.p.m. and a minimum of 75 c.f.m. per locomotive horsepower when Diesel locomotives are operating in virtually normal air; the volume of fresh air required per locomotive horsepower should be increased to maintain a safe concentration of other gases that may be present as a result of gas emanations.

Samples of the general tunnel air should be taken from time to time and chemical analyses made to determine the concentration of nitrogen oxides[25] as well as that of the other gaseous constituents of the tunnel atmosphere.

Experience has demonstrated that acceptable conditions are attainable in the general tunnel air when the carbon monoxide concentration is kept within the range of 0.001 to 0.002 percent by volume and is used as a yardstick for the control of atmospheric conditions.

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[25] See footnote 6 (p. 3), pp. 7-8.
Allison, V. C., Parker, W. L., and Jones, G. W., The Determination of Oxides of Nitrogen: Bureau of Mines Tech. Paper 249, 1921, 12 pp. In the original development of this procedure the gases were absorbed in an alkaline solution; in a later modification of the method an acid solution was used as the absorbent. See Piccard, J., Peterson, E. G., and Bitting, C. D., Determination of Oxides of Nitrogen (Except Nitrous Oxide) in Low Concentrations: Ind. Eng. Chem., anal. ed., vol. 2, 1930, pp. 294-295.